Microwave-induced suppression of dissipative conductivity and its Shubnikov – de Haas oscillations in two-dimensional electron systems: Effect of dynamic electron localization

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We present a model for microwave photoconductivity in two-dimensional electron systems (2DESs) in a magnetic field at the microwave frequencies lower that the electron cyclotron frequency when the intra-Landau level (LL) transitions dominate. Using this model, we explain the effect of decrease in the 2DES dissipative conductivity (and resistivity) and smearing of its Shubnikov – de Haas oscillations by microwave radiation observed recently [1, 2]. The model invokes the concept of suppression of elastic impurity scattering of electrons by the microwave electric field. We calculated the dependence of the 2DES conductivity associated with intra-LL transitions as a function of the radiation and cyclotron frequencies and microwave power. The obtained dependences are consistent with the results of recent experimental observations [1, 2].

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I. INTRODUCTION

Recently, the experimental observations of rather strong effect of relatively low frequency microwave radiation (the radiation frequency $\Omega \lesssim \Omega_c$ or $\Omega \ll \Omega_c$, where Ω_c is the electron cyclotron frequency) on the dissipative conductivity and resistivity of two-dimensional electron systems (2DESs) in GaAs/AlGaAs heterostructures were reported [1, 2]. As shown, at sufficiently high microwave powers, the dissipative conductivity (resistivity) of a 2DES and its Shubnikov – de Haas (SdH) oscillations are substantially suppressed. The modulation of SdH oscillations by microwaves was also reported by other authors (see, in particular, [3]). The observed effect supplements the pattern of microwave-induced transport phenomena in 2DESs related to the microwave-induced zero-resistance and zero-conductance states revealed by Mani *et al.* [4] and Zudov *et al.* [5] and extensively studied both experimentally and theoretically last two years (for early predictions see, for example, Ref. [6]).

Leaving aside the hypothesis put forward in Ref. [1] to clarify the effect, we provide an explanation associated with the suppression of electron scattering on impurities with intra-Landau level (LL) transitions by microwave radiation. The main point is that the ac electric field of microwave (or optical) radiation gives rise to spatio-temporal oscillations of the electron Larmor orbit center that leads to an additional spreading of the wave function. As a result, the matrix elements of electron-impurity interaction, the probability of electron elastic scattering with a displacement of the orbit center, and therefore, the dissipative conductivity are decreased by microwave radiation even without absorption or emission of real photons.

The effect of dissipative conductivity suppression was predicted and assessed theoretically for 3DESs in magnetic field many years ago [7]. Similar effect of radiation-induced suppression of electron transitions between two spatially separated states (in neighboring quantum wells), called the dynamic electron localization, was discussed and experimentally observed by Keay *et al.* [8]. The possible role of the effect of dynamic electron localization in 2DESs in a magnetic field was mentioned in Ref. [9]. In this paper, we present a theoretical model for this effect and assess it. It is demonstrated that invoking the mechanism under consideration one can explain main features of the experimental results.

II. ELECTRON TRANSPORT DUE TO INTRA-LL ELECTRON TRANSITIONS.

The dissipative electron transport in the direction parallel to the electric field and perpendicular to the magnetic field is due to hops of electron orbit centers caused by scattering processes. These hops result in a change in the electron potential energy $\delta\epsilon = -F\delta\rho$, where $F = -eE$ is the dc electric force, E is the dc electric field, and $\delta\rho = \rho_k - \rho_k'$ is the displacement of the electron orbit center. When electron scattering on impurities dominates and LL broadening is insignificant, the displacement of electron orbit center caused by scattering with the electron transition from the state (N, ρ_k) to the state $(N', \rho_{k'})$ one can found using the energy conservation law (disregarding spin-flip effects):

$$F\delta\rho = \Lambda\hbar\Omega_c, \tag{1}$$

where $\Lambda = N' - N$ and $\hbar$ is the reduced Planck constant.. The matrix element, $\mathcal{M}_i$, of the electron transitions due to impurity scattering and, consequently, the probability, $\mathcal{W}$, of the scattering processes in question are determined by the overlap of electron wave functions (6) corresponding to two spatially separated states (i.e., with different

coordinates of the electron orbit center ρ_k) and, therefore, $\mathcal{W} = \mathcal{W}(\delta\rho)$ steeply decreases at sufficiently large $\delta\rho$. Due to this, the pertinent contribution to the dissipative current is

$$\delta J_D \propto -e\delta\rho\mathcal{W}(\delta\rho). \qquad (2)$$

Considering Eqs. (1) and (2) and taking into account electron-impurity interactions in the Born approximation, one can arrive at the following formula for the dissipative current which is equivalent to that obtained by Tavger and Erukhimov [10]:

$$J_D \propto \nu_i \sum_\Lambda (f_N - f_{N+\Lambda}) \left| A^{(i)}_{N,\Lambda}\left(\frac{\hbar\Omega_c}{eEL}\right)\right|^2$$

$$\times \left(\frac{\Lambda\hbar\Omega_c}{eEL}\right) \exp\left[-\frac{1}{2}\left(\frac{\Lambda\hbar\Omega_c}{eEL}\right)^2\right]. \qquad (3)$$

Here ν_i is the frequency characterizing electron-impurity collisions, L is the quantum magnetic length, $A^{(i)}_{N,\Lambda}$ is determined by the matrix elements of the impurity potential, $f_N = [\exp(N\hbar\Omega_c/T - \zeta_F) + 1]^{-1}$ is the Fermi distribution function, $\zeta_F = \varepsilon_F/T$, and ε_F is the 2DES Fermi energy reckoned from the lowest LL and normalized by temperature T.

In a nondegenerate 2DES in moderate electric fields $E < E_c = \hbar\Omega_c/eL$ (so that $eEL < \hbar\Omega_c$), the transitions only between the neighboring ($\Lambda = 1$) LLs with small indices are efficient. In this case, Eq. (3) yields for the dissipative conductivity the following expression:

$$\sigma_D = \frac{J_D}{E} \propto \nu_i \exp\left[-\frac{1}{2}\left(\frac{E_c}{E}\right)^2\right]. \qquad (4)$$

As pointed out, the exponential electric-field dependences given by Eqs. (3) and (4) are due to inter-LL transitions which become crucial under sufficiently strong net dc electric field. Such inter-LL transitions can be called the Zener tunneling transitions between LLs [11]. If the Zener tunneling between LLs is due to resonant transitions via impurity levels [12], the calculated dissipative current-voltage characteristic remains exponential. In a degenerate 2DES with a large filling factor $N_F = \varepsilon_F/\hbar\Omega_c$, the electron inter-LL transitions with $\delta\rho \sim L_F = L\sqrt{2N_F+1}$ can provide the main contribution to the dissipative current (see, for example, [11]). In this case, inter-LL electron transitions become crucial and a substantial increase in the dissipative conductivity occurs when $E \gtrsim E_c^{(F)} = \hbar\Omega_c/L_F \simeq E_c/\sqrt{2N_F}$.

Equation (4) yields a non-analytic electric-field dependence which corresponds to σ_D vanishing in the limit of weak electric field [10]. However, nonanalytical dependences, like that given by Eq. (4), are valid only if $|E| \gg E_b = \hbar\Gamma/eL$, $E_b^{(F)} = \hbar\Gamma/eL_F$,, where Γ is the LL broadening. In relatively weak net dc electric fields, the LL broadening becomes crucial [13]. The dissipative conductivity of 2DESs in a magnetic field associated with impurity scattering under the assumption that LL broadening is due to electron-electron interactions ($\Gamma \simeq \Gamma_{ee} > \Gamma_i \sim \nu_i$) was considered in Ref. [13]. The latter can be justified, in particular, in the 2DESs in which the electron sheet concentration Σ is of the same order of magnitude as the sheet concentration of remote donors (separated from the 2DES by sufficiently thick spacer). In strongly degenerate 2DESs, in which electron-electron scattering is markedly weaken (see, for example, [14]), the contribution of impurity scattering to the LL net broadening can be essential. According to Eq. (1), impurity scattering in weak electric field $|E| \ll E_c, E_c^{(F)}$ can result only in the transitions with rather large $|\delta\rho|$. Due to very small overlap of the electron wave functions in the initial and final states, the probability of these transitions is exponentially small. This leads to an exponentially small contributions of inter-LL transitions to the dissipative current in small dc electric fields. However, in the range of weak electric fields, the dissipative conductivity can be associated with electron scattering on impurities within LLs provided that LLs have a finite width. This implies that although electron-electron interaction does not change the total momentum of the electron system and, hence, does not directly lead to the dissipative conductivity, it may mediate the momentum transfer to the scatterers and, therefore strongly affect electron transport phenomena (see, for example, Ref. [15]). Invoking the mechanism of intra-LL impurity scattering mediated by electron-electron collision, one can understand the association of the dissipative current with the Joule heating of 2DES. Indeed, in the case of the mechanism in question, the change in the electron potential energy associated with the electron orbit centers displacements in the direction of the electric force is compensated by an increase of the kinetic energy (heating) of all participated electrons. The problem of Joule heating in 2DES in a magnetic field, to the best of our knowledge, is not resolved in the framework of model considering solely impurity scattering (even beyond the Born approximation). There is no such a problem in the case of 2DES in a magnetic field because the energy acquired by an electron from the electric field due to the displacement of its Larmor orbit center associated with impurity scattering goes to an increase of the energy of the electron motion along the magnetic field.

When $\Omega_c \gg \Gamma$, the values of characteristic fields E_b and $E_b^{(F)}$, on the one hand, and E_c and $E_c^{(F)}$, on the other, are strongly different. For example, for a AlGaAs/GaAs 2DES, assuming $H = 0.2$ T, $\Gamma = 10^{10}$ s^{-1}, and $N_F = 50$ one can obtain $E_b \simeq 1$ V/cm, $E_b^{(F)} \simeq 0.1$ V/cm, $E_c \simeq 60$ V/cm, and $E_c^{(F)} \simeq 6$ V/cm.

As follows from Ref. [13], in the case $\Gamma < T/\hbar \ll \Omega_c$, the dissipative current (dissipative conductivity) in low

dc electric fields is given by

$$J_D \propto E\nu_i \sum_N b_N^{(i)} \left(-\frac{\partial f_N}{\partial \zeta_F}\right). \tag{5}$$

Here

$$\frac{\partial f_N}{\partial \zeta_F} = \frac{\exp(N\hbar\Omega_c/T - \zeta_F)}{[1+\exp(N\hbar\Omega_c/T - \zeta_F)]^2} \tag{6}$$

and $b_N^{(i)}$ is a coefficient determining by the matrix elements of the impurity potential which, in turn, depend on the LL index. The most crucial feature of the formula for the dissipative current is that the latter is determined by the effective frequency of electron collisions with impurities and by the derivative of the electron distribution function [16].

Using Eq. (5), the low-field dissipative conductivity can be presented as

$$\sigma_D \propto \nu_i \sum_N \frac{b_N \exp(N\hbar\Omega_c/T - \zeta_F)}{[1+\exp(N\hbar\Omega_c/T - \zeta_F)]^2}. \tag{7}$$

As follows from Eq. (6), at $T < \hbar\Omega_c$, the dissipative conductivity is a strongly oscillating function of Ω_c and ζ. This is the well-known effect of SdH oscillations in 2DES (see, for example, Ref. [16]) One can see from Eq. (6) that σ_D reaches maxima when $N\hbar\Omega_c = \varepsilon_F$, whereas the minima of σ_D correspond to $(N+1/2)\hbar\Omega_c = \varepsilon_F$. At the minima,

$$\sigma_D \propto \exp\left(-\frac{\hbar\Omega_c}{2T}\right). \tag{8}$$

Thus, despite the dissipative conductivity in the case of low electric field under consideration is determined by electron transitions within LLs, it exhibits an activation behavior with activation energy $\varepsilon_A = \hbar\Omega_c/2$ which is determined by the separation between LLs. At sufficiently low temperatures, the dissipative conductivity exhibits giant SdH oscillations with its exponentially small values under the condition of quantum Hall effect $N\hbar\Omega_c < \varepsilon_F < (N+1)\hbar\Omega_c$.

III. EFFECT OF MICROWAVES ON INTRA-LL ELECTRON TRANSITIONS

To calculate the contribution of impurity scattering of electrons in the dc electric and magnetic fields in the presence of microwave ac electric filed to the dissipative conductivity, one can start from the following Hamiltonian:

$$\mathcal{H}_{\mathcal{E}} = -\frac{\hbar^2}{2m}\left[\frac{\partial^2}{\partial\rho^2} + \left(\frac{\partial}{\partial\xi} + i\frac{e}{c\hbar}H\rho\right)^2\right] + eE\rho$$

$$+e\mathcal{E}(t)(e_\rho\rho + e_\xi\xi). \tag{9}$$

Here $\mathcal{E}(t) = \mathcal{E}\cos\Omega t$ is the ac electric field of microwave radiation, which is taken into account in the dipole approximation, and e_ρ and e_ξ are the components of the microwave field complex polarization vector. The Hamiltonian (9) leads to quasi-stationary states which are characterized by quasi-energies. The probability of an electron transition from state (N, ρ_k) to state (N', ρ_k') due to the scattering on impurities accompanied with the absorption of M real photons is proportional to

$$|\mathcal{M}^{(M)}_{N,\rho_k,N',\rho_{k'}}|^2 = |J_M(a_\Omega Q)|^2 |\mathcal{M}_{N,\rho_k,N',\rho_{k'}}|^2. \tag{10}$$

Here $\mathcal{M}_{N,\rho_k,N',\rho_{k'}}$ is the matrix element of electron-impurity interaction without microwave radiation, $J_M(x)$ is the Bessel function, $a_\Omega = L_{\mathcal{E}}/L$ is the relative amplitude of electron orbit center classical oscillations in the crossed dc electric and magnetic fields under the ac microwave electric field, and $Q = L(k'-k)$. Thus, the matrix element and, consequently, the probability of an electron transition due to the scattering on impurities accompanied with the absorption or emission of M real photons is proportional to additional factor $|J_M(a_\Omega Q)|^2$. In the case of circular polarization or when the microwave radiation is nonpolarized,

$$L_{\mathcal{E}} = \frac{e\mathcal{E}}{\sqrt{2}m\Omega^2}\frac{\Omega\sqrt{\Omega_c^2+\Omega^2}}{|\Omega_c^2 - \Omega^2|}. \tag{11}$$

The appearance of the Bessel functions in the scattering matrix elements is the result of calculation using the exact wave functions of electrons in both dc and ac fields. This can be attributed to the processes of absorption and emission of arbitrary number of virtual photons in each process involving M real photons. Scattering processes in the presence of microwave ac electric field are characterized by the following two features of photon-assisted impurity scattering processes [7, 9, 17]. First, $|\mathcal{M}^{(M)}_{N,\rho_k,N',\rho_{k'}}|^2$ and, consequently the probability of the processes involving M real photons is not proportional to $|\mathcal{E}|^{2M}$ - it is a more complex function of $\mathcal{E}$ due to the Bessel function dependence. Naturally, at low microwave powers (low ac electric fields), $|J_1(a_\Omega Q)|^2 \propto a_\Omega^2 Q^2$, and the matrix element for single photon processes becomes proportional to $a_\Omega^2 \propto |\mathcal{E}|^2$, i.e., proportional to the microwave power P_Ω. Second, the probability of the impurity scattering of electrons without the absorption of real photons ($M = 0$), i.e., elastic impurity scattering depends, nevertheless, on the microwave field. This effect was theoretically studied in electron systems without and with a magnetic field by different authors many years ago. As pointed out above, microwave radiation can affect intra-LL elastic impurity scattering processes (involving no real photons) in 2DES changing the effective frequency of electron collisions with impurities. Such an effect can be explained by the following: Increase in the ac electric field leads to an increase in the amplitude of the electron Larmor orbit and, consequently, in a smearing of the electron wave function. Due to this,

the integral of the wave functions with the same LL-index before and after the electron scattering and the impurity potential decreases that leads to a decrease in the scattering probability. Indeed, the matrix element of impurity scattering without absorption or emission of real photons ($M = 0$) is proportional to $|J_0(a_\Omega Q)|^2$. As a result, generally $|\mathcal{M}^{(0)}_{N,\rho_k,N',\rho_{k'}}|^2 \neq |\mathcal{M}_{N,\rho_k,N',\rho_{k'}}|^2$ if $a_\Omega \neq 0$. Consequently, matrix element $\mathcal{M}^{(0)}_{N,\rho_k,N',\rho_{k'}}$ decreases (exhibiting damping oscillations) with increasing $a_\Omega Q$ and even turns zero at $a_\Omega Q \simeq 2.4$. This implies that microwave radiation can effectively suppress inter-LL impurity scattering and, consequently, the hops of electron orbit centers. The latter can be interpreted as some kind of electron localization by microwave radiation resulting in a decrease in the dissipative conductivity outside the cyclotron resonance and its harmonics (compare with the effect of radiation-induced suppression of tunneling between quantum wells [8]). The effect dynamic localization can be particularly important at relatively low microwave frequencies $\Omega < \Omega_c$ when the dissipative conductivity is mainly due to intra-LL impurity scattering processes (the photon energy is insufficient for the inter-LL transitions).

Let the Fourier component of the impurity potential to be $V_q = V_i Q^s \exp(-d_i Q/L)$, where $Q = \sqrt{Q_x^2 + Q_y^2}$. Here V_i is a constant (so that $\nu_i \propto |V_i|^2$) and (a) for charged remote impurities, $s = -1$ and d_i is the spacing between the 2DES and the δ-doped impurity layer, and (b) for short-range residual impurities $s = 0$ and $d_i = 0$. After that, for coefficients b_N in Eq. (7) one can obtain [9]

$$b_N = \frac{1}{\pi}\int dQ_x\, dQ_y Q_y^2 Q^{2s} J_0^2(\xi_\Omega Q)$$

$$\times \exp\biggl(-\beta Q - \frac{Q^2}{2}\biggr)\biggl[L_N^0\biggl(\frac{Q^2}{2}\biggr)\biggr]^2$$

$$= \int_0^\infty dQ J_0^2(a_\Omega Q) Q^{3+2s} \exp\biggl(-\beta Q - \frac{Q^2}{2}\biggr)\biggl[L_N^0\biggl(\frac{Q^2}{2}\biggr)\biggr]^2, \tag{12}$$

where $\beta = 2d_i/L$. At $s = -1$ and $\beta \ll 1$ in the absence of microwave radiation ($a_\Omega = 0$), from Eq. (12) one obtains $b_N = b_N^0$ with

$$b_N^0 = \int_0^\infty dQQ \exp\biggl(-\frac{Q^2}{2}\biggr)\biggl[L_N^0\biggl(\frac{Q^2}{2}\biggr)\biggr]^2 = 1. \tag{13}$$

For the case $s = 0$ and $\beta = 0$, instead of Eq. (12), one obtains

$$b_N^0 = \int_0^\infty dQQ^3 \exp\biggl(-\frac{Q^2}{2}\biggr)\biggl[L_N^0\biggl(\frac{Q^2}{2}\biggr)\biggr]^2$$

$$= 2(2N+1). \tag{14}$$

The latter formula implies that in the case of short-range impurity scattering, the contribution of the transitions within the Nth LL is proportional to the square of the electron Larmor orbit radius $R_N = \sqrt{2N+1}L$. Comparing Eqs. (13) and (14), one can see that the short-range impurity scattering provides a larger contribution to the dissipative conductivity by factor $2(2N+1)$ (for the same impurity concentrations). An increase in the spacer thickness d_i, i.e., an increase of parameter β lead for an additional decrease in the contribution of scattering on charged impurities. This is consistent with the previous conclusions [9, 17].

At not too high microwave powers and not too close to the cyclotron resonance, one can expand the Bessel function in the right-hand side of Eq. (12). As a result, for the cases of electron scattering on charged impurities ($s = -1$, $\beta \ll 1$) and short-range scatterers ($s = 0$) we arrive, respectively, at

$$b_N \simeq \int_0^\infty dQQ\biggl(1 - \frac{1}{2}\xi_\Omega^2 Q^2\biggr)\exp\biggl(-\frac{Q^2}{2}\biggr)\biggl[L_N^0\biggl(\frac{Q^2}{2}\biggr)\biggr]^2$$

$$= 1 - \frac{1}{2}a_\Omega^2 \int_0^\infty dQQ^3 \exp\biggl(-\frac{Q^2}{2}\biggr)\biggl[L_N^0\biggl(\frac{Q^2}{2}\biggr)\biggr]^2$$

$$= 1 - (2N+1)a_\Omega^2. \tag{15}$$

$$b_N \simeq \int_0^\infty dQQ^3\biggl(1 - \frac{1}{2}a_\Omega^2 Q^2\biggr)\exp\biggl(-\frac{Q^2}{2}\biggr)\biggl[L_N^0\biggl(\frac{Q^2}{2}\biggr)\biggr]^2$$

$$= 2(2N+1) - \frac{1}{2}\xi_\Omega^2 \int_0^\infty dQQ^5 \exp\biggl(-\frac{Q^2}{2}\biggr)\biggl[L_N^0\biggl(\frac{Q^2}{2}\biggr)\biggr]^2$$

$$= 2(2N+1) - 4(3N^2+3N+1)a_\Omega^2 \simeq 4N(1 - 3Na_\Omega^2). \tag{16}$$

Assuming that the Fermi energy significantly exceeds the splitting between LLs (large filling numbers), so that the LL with large N are most important, Eq. (16) can be rewritten as

$$b_N \simeq b_N^0\biggl[1 - 2\biggl(\frac{3N^2+3N+1}{2N+1}\biggr)a_\Omega^2\biggr]$$

$$\simeq b_N^0(1 - 3Na_\Omega^2). \tag{17}$$

Considering Eqs. (13) - (17), we obtain

$$b_N \simeq b_N^0\biggl[1 - k(s,\beta)N\biggl(\frac{2\pi\alpha P_\Omega}{m\Omega^3}\biggr)\mathcal{F}(\Omega_c/\Omega)\biggr], \tag{18}$$

where $\alpha = e^2/\hbar c \simeq 1/137$, as follows from Eqs. (16) and (17), $k(-1,0) \simeq 2$ and $k(0,0) \simeq 3$, and $\mathcal{F}(\omega_c) = \omega_c^2(\omega_c^2+1)/(\omega_c^2-1)^2$. Using Eqs. (7) and (18) and

taking into account that the main contributions to the dissipative conductivity are due to intra-LL transitions within several LLs in the vicinity of the Fermi energy (i.e., within the LLs with $N \simeq \varepsilon_F/\hbar\Omega_c$), we obtain the following formula for the dissipative conductivity associated with intra-LL electron scattering on impurities in the presence of microwave radiation:

$$\sigma_D \simeq \sigma_D^0[1 - \mathcal{P}\,\mathcal{F}(\Omega_c/\Omega)], \qquad (19)$$

where σ_D^0 is the dark dissipative conductivity exhibiting SdH oscillations with varying Ω_c. The introduced normalized microwave power $\mathcal{P}$ is given by $\mathcal{P} = P_\Omega/\overline{P_\Omega}$, where

$$\overline{P_\Omega} = \frac{m\Omega^4\hbar}{2\pi\alpha k(s,\beta)\varepsilon_F} \qquad (20)$$

Setting the electron effective mass $m = 6 \times 10^{-29}$ g (GaAs), the electron sheet density $\Sigma = 3 \times 10^{11}$ cm^2 (as in Ref. [1]), and $s = 0$, at the microwave frequency $f = \Omega/2\pi = 20$ GHz, one can find $\overline{P_\Omega} \simeq 0.69$ mW/cm^2. If $\Omega = const$, the normalized dissipative conductivity (and, consequently, normalized resistivity) changes from $\sigma_D/\sigma_D^0 = 1 - \mathcal{P}/2\Delta$ at $\Omega_c/\Omega = 1 + \Delta \gtrsim 1$, where $\Delta \ll 1$ (but $\Delta \gtrsim \Gamma/\Omega_c$), to $\sigma_D/\sigma_D^0 = 1 - \mathcal{P}$ at $\Omega_c \gg \Omega$, i.e., $\Delta \gg 1$. In particular, at $\Delta = 0.2$ and $\Delta = 2.0$, Eq. (19) yields $\sigma_D/\sigma_D^0 - 1 \simeq -18\mathcal{P}$ and $\sigma_D/\sigma_D^0 - 1 \simeq -2.2\mathcal{P}$, respectively. At elevated microwave powers, the dependence of σ_D on $\mathcal{P}$ becomes nonlinear.

IV. RESULTS AND DISCUSSION

As follows from Eq. (20), the microwave radiation suppresses the dissipative conductivity. It decreases both the averaged (smooth) value of the dissipative conductivity and the amplitude of its oscillations. Figures 1 - 3 demonstrate the dependences of the normalized dissipative conductivity of the 2DES dissipative conductivity associated with the intra-LL electron transitions in dark conditions and under microwave radiation calculated using the formulas obtained above on ratio Ω_c/Ω. At fixed microwave frequency Ω, these dependences are actually the magnetic-field dependences. In the vicinity of the cyclotron resonance, to take into account the LL damping, function $\mathcal{F}(\omega_c)$ is replaced by $\mathcal{F}^*(\omega_c) = \omega_c^2(\omega_c^2+1)/[(\omega_c^2-1)^2+\gamma^2]$, where $\gamma = 2\Gamma/\Omega$. The dissipative conductivity is normalized by its value in the absence of microwave radiation at such a magnetic field that $\Omega_c = \Omega$. It is assumed that the electron sheet concentration in the 2DES is equal to $\Sigma = 3 \times 10^{11}$ cm^{-2}, so that setting $\varepsilon_F = \pi\hbar^2\Sigma/m$, where m is the electron effective mass, at $T = 0.4$ K one obtains $\zeta_F \simeq 280$. Apart from this, we set $\Gamma/\Omega_c = 0.02$, $s = 0$, and $d_i = 0$ (short-range impurity scattering) in Figs. 1 and 2. In Fig. 3, the curves correspond to the cases of both short-range and long-range impurity scattering. As seen from Fig. 1, at fixed microwave frequency Ω, the degree of suppression

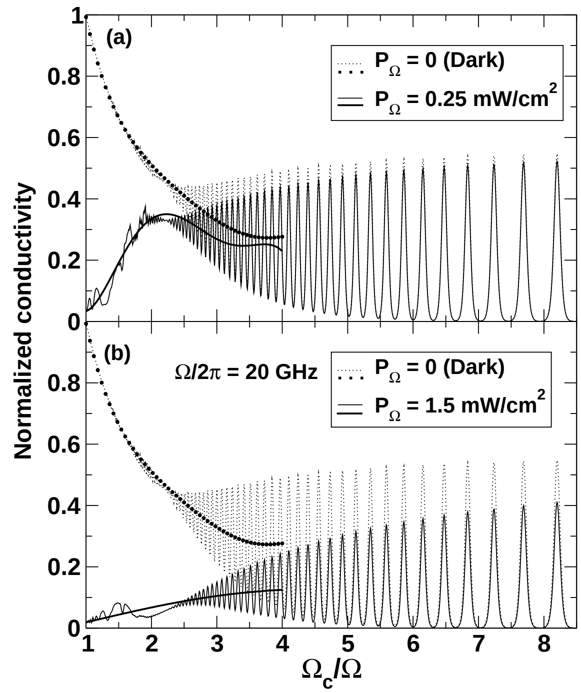

FIG. 1: Magnetic-field dependences of dissipative conductivity associated with intra-LL processes normalized by dark dissipative conductivity at $\Omega_c = \Omega$ at fixed microwave frequency and different microwave powers. The conductivity averaged over SdH oscillations is show by bold dotted (dark conductivity) and solid (conductivity in presence of microwave radiation) curves.

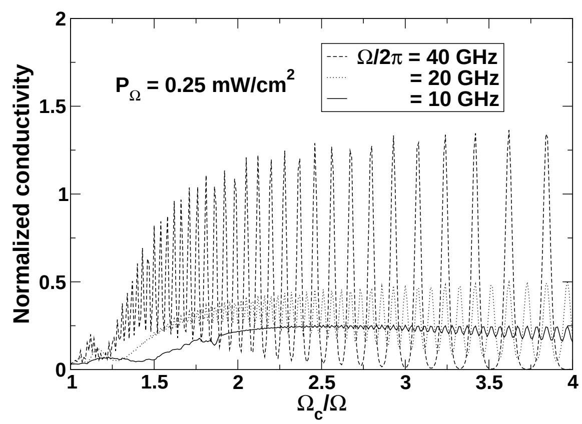

FIG. 2: Normalized magnetic-field dependences of intra-LL conductivity at different microwave frequencies.

increases with increasing microwave power and decreases with increasing cyclotron frequency, i.e., when the magnetic field becomes stronger. One needs to stress that in the vicinity of the cyclotron resonance ($\Omega_c/\Omega \gtrsim 1$), the contribution of the inter-LL photon assisted scattering on impurities (which is not shown in Figs. (1) - (3)) is substantial. However, this contribution rapidly decreases when Ω_c/Ω deviates from unity.

Figure 2 shows that the effect of dissipative conductiv-

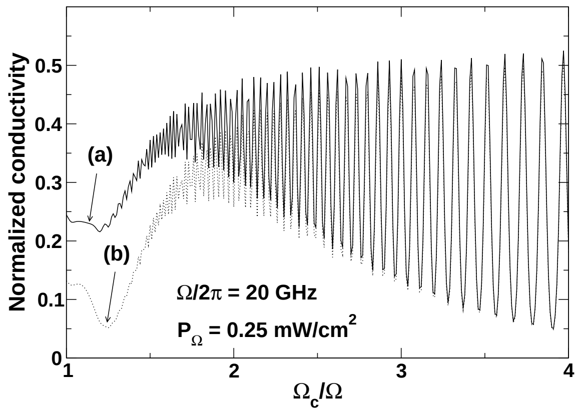

FIG. 3: Normalized magnetic-field dependences of intra-LL conductivity calculated for (a) long-range and (b) short-range impurity scattering mechanisms.

ity decrease and suppression of its SdH oscillations being rather strong at relatively low microwave frequencies (for example, at $f = 10 - 20$ GHz) markedly weakens with increasing microwave frequency. Indeed, as seen from Fig. 2, at $f = 10\ GHz$ the average conductivity is relatively small, and its SdH oscillations are almost smeared. However, an increase in the microwave frequency to $f = 40$ GHz leads to marked increase of the average conductivity and recovery of SDH oscillations. One can see that the amplitude of electron orbit center oscillations in the limit $\Omega_c \gg \Omega$ is inversely proportional to both Ω_c and Ω. As follows from Eq. (11), in this case, $L_{\mathcal{E}} \propto \mathcal{E}/\Omega_c\Omega$ [18]. Hence, an increase in either Ω_c or Ω results in vanishing of the effect of microwave radiation on intra-LL conductivity. This is consistent with the experimental observations [1, 2].

As found in the previous section, the strength of the effect of microwave suppression under consideration depends on the dominating impurity scattering mechanism; the effect is more pronounced when electrons are scattered primarily due a short-range interaction with impurities. This is confirmed by the results of calculations shown in Fig. 3.

One needs to point out that Figs. (1) - (3) show the contribution to the 2DES dissipative conductivity associated with intra-LL electron transitions. When Ω_c is moderately larger than Ω, photon-assisted inter-LL scattering processes significantly contribute to the conductivity. Since this contribution (at $\Omega_c \gtrsim \Omega$) is positive and it is of the resonant nature, this resonant contribution surpasses the contribution of intra-LL transitions in the immediate vicinity of cyclotron resonance as seen on the experimental plots [1]. However, when $\Omega_c > \Omega$, the effect of dynamic suppression of electron intra-LL scattering is dominant. At higher magnetic fields when Ω_c markedly exceeds Ω, the effect of microwaves on the scattering being still dominant becomes weaker because of a decrease in the amplitude of electron oscillations in the microwave ac electric field with increasing magnetic field.

An increase in the electron temperature due to microwave heating can affect the dissipative conductivity of 2DESs as well. However, the electron heating leads to smearing SdH oscillations but it does not change or slightly increases (see, for example, [16] and references therein), the dissipative conductivity averaged over these oscillations at least until the electron temperature remains small compared to the Fermi energy. However, a marked decrease in the dissipative conductivity averaged over SdH oscillations was observed [1, 2]. Due to this, the heating mechanism appears to be irrelevant to the effect observed experimentally in Refs. [1, 2], although this mechanism requires further theoretical analysis.

V. CONCLUSIONS

We proposed a model for low-frequency microwave photoconductivity in 2DESs in a magnetic field based on the concept of dynamic localization of electrons by microwave ac electric field. We showed that this model explains the following features of of microwave photoconductivity:
(1) Effective suppression of the dissipative conductivity and its SdH oscillations by microwave radiation with sufficiently high power in wide magnetic field range corresponding to Ω_c/Ω somewhat exceeding;
(2) Reincarnation of SdH oscillations at sufficiently large ratio Ω_c/Ω.

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[1] S. I. Dorozhkin, J. Smet, V. Umansky, and K. von. Klitzing, cond-mat/0409228 (2004).
[2] R. G. Mani, cond-mat/0410227 (2004).
[3] R. R. Du, M. A. Zudov, C. L. Yang, Z. Q. Yuan, L. N. Pfeifer, and K. W. West, cond-mat/0409409 (2004).
[4] R. G. Mani, J. H. Smet, K. von Klitzing, V. Narayanamurti, W. B. Johnson, and V. Umanski, Natrure **420**, 646 (2002).
[5] M.A.Zudov, R.R.Du, L.N.Pfeiffer, and K.W.West, Phys. Rev. Lett. **90**, 046807 (2003).
[6] V. I. Ryzhii, Fiz. Tverd. Tela **11**, 2577 (1969) [Sov. Phys.-Solid State **11**, 2078 (1970)].
[7] A. D. Malov and V. I. Ryzhii, Fiz. Tverd. Tela **14**, 2048

(1972) [Sov. Phys. Solid State **14**, 1766 (1973)].

[8] B. J. Keay, S. Zeuner, S. J. Allen Jr, K. D. Maranowski, A. S. Gossard, U. Bhattacharya, and M. J. W. Rodwell, Phys. Rev. Lett. **75**, 4102 (1995).

[9] V. Ryzhii and R. Suris, J. Phys. Cond. Mat. **15**, 6855 (2003).

[10] B. A. Tavger and M. Sh. Erukhimov, Zh. Eksp. Teor. Fiz. **51**, 528 (1966) [Sov. Phys. JETP **24**, 354 (1967)].

[11] C. L. Yang, J. Zhang, R. R. Du, J. A. Simmons, and J. L. Reno, Phys. Rev. Lett. **89**, 076801 (2002).

[12] V. L. Pokrovsky, L. P. Pryadko, and A. L. Talapov, J. Phys. Cond. Mat. **2**, 1583 (1990).

[13] V. I. Ryzhii, Fiz. Tekh. Poluprovodn. **3**, 1704 (1969) [Sov. Phys. Semicond. **3**, 1432 (1970)]; V. I. Ryzhii, Dissertation, Moscow, MPhTI, 1970 (unpublished).

[14] A. V. Chaplik Zh. Eks. Teor. Fiz. **60**, 997 (1971) [Sov. Phys. JETP **33**,997 (1971)].

[15] M. I. Dykman and L. P. Pryadko, Phys. Rev. **67**, 235104 (2003).

[16] T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).

[17] X. L. Lei, J. Phys. Cond. Mat. **16**, 4045 (2004).

[18] At microwave frequencies much smaller than the cyclotron frequency, the oscillations of electron orbit center are mainly due to its Hall drift in the ac electric field. In this case, the amplitude of such oscillations $L_{\mathcal{E}} \sim v_{\mathcal{E}}/\Omega$, where $v_{\mathcal{E}} = c\mathcal{E}/H \propto \mathcal{E}/\Omega_c$ is the Hall velocity in the crossed ac electric and dc magnetic fields and c is the speed of light. As a result, $L_{\mathcal{E}} \propto \mathcal{E}/\Omega_c\Omega$.